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THE INSTITUTE OF PAPER CHEMISTRY

Appleton, Wisconsin

EFFECT OF SPECIMEN DIMENSIONS ON EDGEWISE COMPRESSION TESTS OF LINERBOARD

Part II

Project 1108-4

A Preliminary Report

to

TECHNICAL DIVISION
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SUMMARY

A study is in progress to determine the effect of specimen dimensions on the modified ring compression test of linerboard and corrugating medium. Previously reported work with a sample of 42-lb. linerboard revealed that the maximum load (cross direction) is independent of specimen height when the height is in the range of 0.4 to 1.2 inches. This result indicates that a primary criterion for an adequate edgewise compression test is satisfied, namely, that the specimen undergoes direct edgewise compression rather than compression instability (buckling).

Analogous study of the effect of height on the regular ring compression test and the Concora liner tests (CLT) on the same sample of 42-lb. linerboard reveals the following:

1. Neither the regular ring nor the CLT exhibited a range of short heights where load was independent of height. Thus, neither test satisfies the above-mentioned criterion for a suitable edgewise compression test.

2. The maximum load of the regular ring specimens decreased approximately linearly as height was increased in the range of 0.4 to 1.5 inches.

3. All of the regular ring specimens suffered crushing of a loading edge and bending of the free vertical edges, the latter becoming progressively more pronounced as the height was increased.

4. The maximum load of the CLT specimens decreased markedly ~~rapidly~~ as the height was increased from 0.4 to 1.6 inches. At heights of one inch and larger the maximum load was less than one pound per inch of width.

5. All of the CLT specimens suffered bending failure (compression instability or buckling). The observed failure load and the theoretical buckling load of these specimens agreed to 11%, on the average, lending further support to the observation that the CLT fails by compression instability.

INTRODUCTION

A primary requirement of an adequate edgewise compression test of linerboard and corrugating medium is that the specimen undergoes edgewise compression failure rather than compression instability (buckling or bending). Observation of the mode of failure is one way of determining whether or not the specimen meets the above-mentioned criterion. Another way is to study the behavior of the specimen over a range of short heights. If the specimen exhibits edgewise compression, the maximum load should be constant over a range of short heights. On the other hand, if compression instability occurs, the maximum load should vary with height.

Previous work (1) with a sample of 42-lb. linerboard showed that the maximum load of the modified ring compression test (cross direction) is independent of specimen height in the range of 0.4 to 1.2 inches. This result satisfies the above-mentioned criterion for an adequate edgewise compression test, namely the occurrence of edgewise compression failure rather than compression instability (buckling) in the specimen.

This report presents the results of analogous studies of the effect of specimen height on two other types of tests which have been used to evaluate edgewise compression strength — the regular ring compression test and the Concora liner test (CLT).

The above studies are one phase of an investigation of the effect of specimen dimensions on edgewise compression tests of linerboard and corrugating medium. Work is in progress relative to the effect of specimen radius, thickness, and modulus of elasticity on the modified ring compression test and will be described in a forthcoming report. ~~Additional study of the effect of height is also underway for linerboard grades heavier and lighter than 42 lb. to confirm earlier results.~~

TEST PROCEDURE

The same sample of 42-lb. linerboard used in the earlier study of modified ring compression (1) was employed in the present work. After standard conditioning, cross-direction regular ring specimens and Concora liner test specimens were prepared with heights listed in Table I. The length of the specimens was six inches in all cases. The height dimension was cut with a precision strip cutter, with the exception of the 0.5-inch high specimens which were cut on a Concora die-cutter.

TABLE I

HEIGHT OF REGULAR RING AND CONCORA LINER TEST SPECIMENS

		Number of Specimens		
		Regular Ring		
Sample	Height, in.	Bottom Holder Only	Top and Bottom Holder	CLT
A	0.394	10 + 10 retest	–	10
B	0.500	10 + 10 retest	–	10
C	0.591	10 + 10 retest	–	10
D	0.788	10	–	10
E	1.000	10	5	10
F	1.182	10	–	10
G	1.576	10	5	10
H	1.773	–	10	–
I	2.364	–	10	–
J	3.000	–	10	–

All specimens were tested in a Baldwin-Southwark Universal testing machine at a strain rate of 0.010 in./in./min. The bottom edge of the regular ring specimens was inserted in an ASTM-type holder with an island diameter appropriate to the thickness of the liner. For reasons discussed later, repeat tests were performed at the three shortest heights (Samples A through C) for regular ring. As the height of the regular rings increased, it became increasingly difficult to maintain a cylindrical specimen by means of the bottom holder; the top of the specimen spread open, giving the specimen a conical shape. To overcome this, a second holder was mounted to the top platen of the testing machine directly above the lower holder (with the island secured to prevent falling out of the upper holder). The taller samples (E through J) were tested after slipping the specimen into both holders, thereby keeping the specimen cylindrical at the start of the test.

The Concora liner test specimens were tested in the approved holder. The straightening device which is normally used in an H & D tester to overcome curl was adapted to the upper platen of the Baldwin testing machine. Sample A had to be tested without the straightening device because it was too short for the available clearance between the CLT holder and the straightening device; however, curl should be less of a problem at this short height, namely 0.394 inch, which is a free span of 0.144 inch.

DISCUSSION OF RESULTS

The average maximum loads sustained by the regular ring and CLT specimens (cross direction) are listed in Table II along with the modified ring loads previously given in Reference (1). A graph of load vs. height for the three types of tests is given in Fig. 1.

TABLE II

EDGEWISE COMPRESSION LOADS OF MODIFIED RING, REGULAR RING, AND CONCORA LINER TEST FOR VARIOUS SPECIMEN HEIGHTS

		Maximum Load, lb./in.			
			Regular Ring		
Sample	Height, in.	Modified Ring	Bottom Holder Only	Top and Bottom Holder	CLT
A	0.394	15.79	13.33 (13.21)[a]	–	8.62
B	0.500	15.77	13.94 (14.01)[a]	–	6.80
C	0.591	15.76	12.79 (13.17)[a]	–	3.84
D	0.788	15.83	11.79	–	1.84
E	1.000	15.26	11.16	12.67	0.98
F	1.182	15.90	10.47	–	0.64
G	1.576	14.36	9.45	10.53	0.29
H	1.773	14.84	–	10.59	–
I	2.364	14.06	–	10.98	–
J	3.000	13.91	–	10.14	–

[a]Retest.

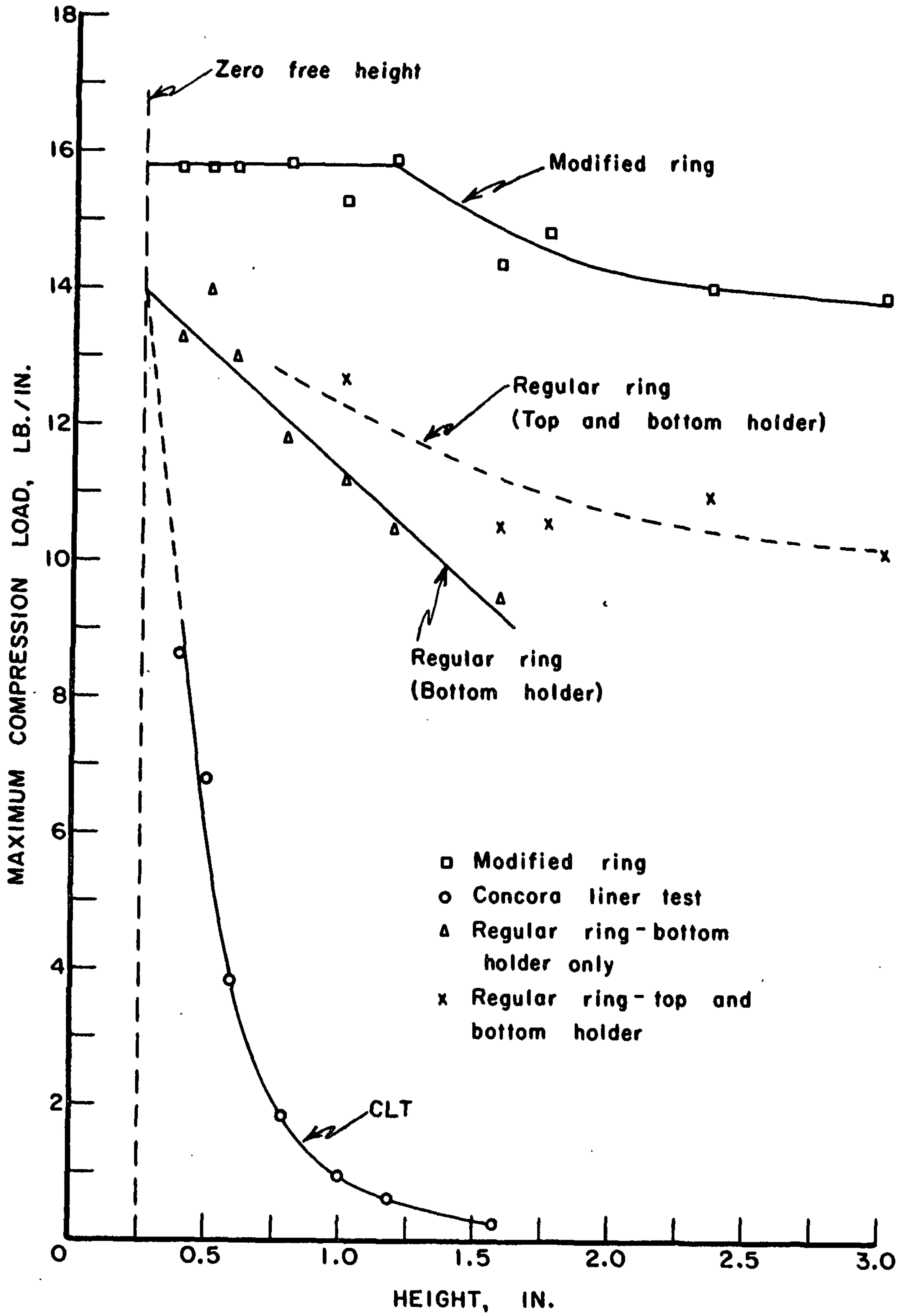

Figure 1. Relationship between Maximum Load and Specimen Height for Modified Ring, Regular Ring and Concora Liner Tests (42-lb. Kraft Linerboard, Cross-Direction).

It may be seen that the maximum load of the regular rings (bottom holder only) decreased almost linearly with increase in height of the specimen. This is in contrast to the loads of the modified ring which, with one exception, are constant over the range of the six smallest heights.

Special attention is warranted for Sample B (0.5-inch height) of the regular ring. The initial tests gave a substantially higher load than the next shorter and next taller samples (Samples A and C). A retest of these three samples confirmed the trend as shown in Table II. Statistical analysis reveals that Sample B is significantly higher (0.05 level) than Sample A (and also higher than the average of Samples A and C). Thus, Sample B differs from the trend of the remaining regular rings by more than can be attributed to the inherent variability of the regular ring test.

It is believed that this behavior is attributable to having cut specimens of Sample B on a Concora die-cutter and the remaining samples on a different cutter. It may be recalled (2) that the cutting tool is a major factor in the strength of compression specimens which fail by localized crushing of a loading edge, which is the way these regular ring specimens failed. Various cutting tools (or varying degrees of sharpness of a tool) apparently weaken the loading edge to different degrees and this is reflected in the maximum load of the compression test. It appears that the Institute strip cutter weakens the loading edge more than the Concora die-cutter and thereby accounts for the significantly higher load for Sample B. On this premise, the point for Sample B was ignored when visually fitting a straight line to the points for the remaining regular ring samples in Fig. 1. Cutting tool doesn't influence the modified ring because the edge is reinforced and does not fail.

As drawn, the line terminates at a specimen height of 0.25 inch, which corresponds to zero free span and thus is the limiting height for the regular ring test. It is believed that the intercept of the ring compression line on the dashed vertical line at a height of 0.25 inch represents the strength of the loading edges of the specimen. This appears to be 14 lb./in. At greater height, the regular ring specimen sustains less load because of the bowing of the free vertical edges, and this latter effect increases with increasing height.

All of the ring specimens tested with the bottom island suffered localized crushing of a loading edge. In addition, bending of the unsupported vertical edges of the specimen was in evidence and increasingly so as the height was increased. These tests were terminated with Sample G (1.576-in. height) because of the inability of the bottom holder to keep the specimen cylindrical at the start of the test. For the taller samples of the study a holder was used at both the top and the bottom of the specimen, as described in Test Procedure. This method materially improved the performance of the specimen, as may be seen in Table II for Samples E and G where both methods were used. This increase in load can be attributed to the additional support given to the free vertical edges by the top holder. A curve has been faired-in to the data of Fig. 1 for the samples with top and bottom holders. The curve indicates that load varies inversely with height, as would be expected of a column-type structure. All of these specimens with top and bottom holders exhibited crushing of a loading edge, as is typical of the regular ring specimen. Moreover, the free vertical edges buckled perceptibly in several of the specimens of each height.

Concluding this discussion of the regular ring, it may be remarked that the highest load attained by a regular ring sample (13.97 lb./in. for Sample B) is 11.6% lower than the average strength of the short modified rings (average of Samples A, B, C, D, F – namely, 15.81 lb./in.). This difference compares favorably with an average difference of 15.1% exhibited by a large collection of linerboard samples in Reference (3), indicating that the present results are compatible with previous experience.

The above-mentioned results indicate that the regular ring compression test does not satisfy the criterion for an edgewise compression test of linerboard. That is, there was no evidence of a range of short heights over which edgewise compression failure rather than instability occurs. Moreover, it was observed that the specimen fails by localized crushing of a loading edge and buckling of the free vertical edges; neither of these modes of failure is representative of the true edgewise compression strength of the linerboard.

Turning attention to the Concora liner test, it may be seen in Table II or Fig. 1 that the maximum load falls off markedly ~~rapidly~~ with increase in height. Testing was terminated with Sample G (1.576 inches) because the maximum load had decreased to a fraction of a pound per inch.

All of the CLT specimens exhibited bending failure. Clearly, within the range of heights studied here, there is no indication that the CLT specimen attains the edgewise compression strength of the liner, either on the basis of magnitude of load (*cf.* modified ring test) or by the criterion of load being independent of height for short heights or by the nature of failure.

The trend of the curve in Fig. 1 suggests that there might be substantial increase in load as the height is further reduced below 0.394 inch, as indicated by the dashed curve. It is conjectured that for such a further reduction in height the CLT curve would continue to rise steeply to the terminal point of the regular ring compression curve (14 lb./in.), representing edge crush rather than buckling failure of the CLT specimen.

That is, it is believed that in the limiting case of zero free span, both the CLT and regular ring specimens would reach a load corresponding to the strength of the prepared loading edges of the specimen — this strength being less than the edgewise compression strength of the linerboard as measured by the modified ring compression test, which has been found to meet the criteria of an edgewise compression test. As the free span is increased from "zero" the CLT specimen loses strength rapidly because of buckling over its entire width. The regular ring specimen also loses strength as height increases but not as rapidly as the CLT because most of the ring specimen, by virtue of its cylindrical configuration, is relatively more stable than the CLT specimen — only the free vertical edges of the regular ring specimen depreciate the strength of the specimen below the strength of the loading edges.

The maximum load for the conventional CLT specimens (0.5-in. height) was 6.80 lb./in. This load is 57% less than the strength of short modified ring specimens, and this difference compares favorably with past experience (3) where the average difference was 59.5% for a large group of samples having basis weight of 52 lb./1000 sq.ft. or less. Thus, in this regard, the results of the present study are in line with previous experience.

Because of the prevalence of bending (compression instability) of all of the CLT specimens, it may be of interest to compare the observed loads with the theoretical buckling load. The latter is given by the following formula (4):

$$P_{cr} = \frac{\pi^2}{1 - \mu^2} \frac{Et}{(H/\rho \sqrt{C})^2} = \frac{C\pi^2}{12(1 - \mu^2)} \frac{Et^3}{H^2} \tag{1}$$

where $\underline{P_{cr}}$ = critical buckling load, lb./in.

$\underline{E}$ = modulus of elasticity, lb./sq.in.

$\underline{t}$ = thickness, in.

$\underline{H}$ = height, in.

ρ = radius of gyration of cross section about neutral axis = $\underline{t}/\sqrt{12}$, in.

$\underline{C}$ = end fixity coefficient

μ = Poisson's ratio

Equation (1) pertains to a "plate-column." This is a compression structure that has the characteristics of a column in the sense that the unloaded edges of the plate are free (in contrast to the usual concept of a rectangular plate as being restrained in some manner at all four edges). On the other hand, the fixity of the loading edges over the appreciable width of the plate has the effect of increasing the stiffness from $\underline{Et}^3/12$ of a column to $\underline{Et}^3/12(1 - \mu^2)$. With the latter modification, Equation (1) is seen to be the familiar formula for buckling of a column. The CLT specimen fits the above description because its width is large relative to its height and the lateral edges are free.

Except for height, $\underline{H}$, all factors in Equation (1) are constant for the CLT specimens of this study and are taken as the following:

$\underline{E}$ = 157,400 lb./sq.in.

$\underline{t}$ = 0.0126 in.

μ = 0.25

$\underline{C}$ = 2.0

E and t were evaluated for this sample of 42-lb. liner in connection with earlier work (1). Poisson's ratio, μ, of 0.25 is a guess; however, the buckling load is not very sensitive to modest change in μ — a Poisson's ratio of 0.35, for example, would change the results by only 6%. An end fixity coefficient, C = 2.0, applies to a column with one end fixed and the other end hinged and horizontally constrained directly above the fixed end (5). A CLT specimen would appear to fit this description quite well. It should be noted that H in Equation (1) is the free height of the column above the lower clamp, that is, the specimen height minus 0.25 inch.

The calculated buckling load for each CLT sample is listed in Table III along with the observed maximum load. It may be seen that there is good agreement between observed and estimated buckling loads at the greater heights. At the shorter heights the observed loads are not as high as would be anticipated from buckling theory. On the average, the observed loads are within about +11% of the theoretical buckling load. This result fortifies the observations of specimen failure, namely, that the CLT specimen fails by compression instability and thus does not attain the edgewise compression strength of the linerboard.

TABLE III

COMPARISON OF OBSERVED AND ESTIMATED MAXIMUM LOAD
OF CLT SPECIMENS AT VARIOUS HEIGHT

Sample	Height, in.	Unsupported Height, in.	Maximum Load, lb./in. Observed	Estimated	Diff., %
A	0.394	0.144	8.62	—[a]	—
B	0.500	0.250	6.80	8.84	+ 30.0
C	0.591	0.341	3.84	4.75	+ 23.7
D	0.788	0.538	1.84	1.91	+ 3.8
E	1.000	0.750	0.98	0.98	0.0
F	1.182	0.932	0.64	0.64	0.0
G	1.576	1.326	0.29	0.31	+ 6.9
				Average	+ 10.7

[a]Not estimated because theoretical buckling load is in the inelastic range. (Proportional limit = 12.2 lb./in.)

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